



Repowering of an Existing Power Plant by Means of Gas Turbine and Solid Oxide Fuel Cell

Rokni, Masoud

Published in:
Proceedings of the 9th Annual Green Energy Conference (IGEC2014)

Publication date:
2014

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Rokni, M. (2014). Repowering of an Existing Power Plant by Means of Gas Turbine and Solid Oxide Fuel Cell. In *Proceedings of the 9th Annual Green Energy Conference (IGEC2014)* (pp. 410-423)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

REPOWERING OF AN EXISTING POWER PLANT BY MEANS OF GAS TURBINES AND SOLID OXIDE FUEL CELL

Masoud Rokni

Technical University of Denmark, Dept. of Mechanical Engineering, Thermal Energy Section
Building 403, 2800 Kgs. Lyngby, Denmark
e-mail: MR@mek.dtu.dk

ABSTRACT

Repowering is a process consisting in a transformation of an old power plant in order to have a greater nameplate capacity or more efficiency, which result in a net increase of power generated. As a consequence of the higher efficiency, the repowered plant is characterized by higher power output and less specific CO₂ emissions.

Usually, a repowering is performed adding one or more gas turbines to an existing steam cycle which was built decades ago. Thus, traditional repowering results in combined cycles (CC). High temperature fuel cells (such as SOFC) could also be used as a topping cycle, reaching global plant efficiency even higher and specific CO₂ emissions even lower. Decreasing the operating temperature in a SOFC allows the use of less complex materials and construction methods, consequently reducing plant and the electricity cost. A lower working temperature makes it also suitable for topping an existing steam cycle, instead of gas turbine on the top. This is also the target of this study, repowering of an existing power plant with SOFC as well as gas turbines.

The plant used here for repowering is the Kyndby power station is an emergency and peak load facility for Zealand in Denmark. This means the facilities at the station can be started up within minutes if operational irregularities occur in the high voltage electricity grid or problems arise at other power stations. Nowadays this station is repowered with two gas turbines but the current study is about the original steam plant before repowering.

Different repowering strategies are studied here, repowering by one gas turbine with and without supplementary firing, repowering by two gas turbines with and without supplementary firing and repowering using SOFC. Plant performances and CO₂ emissions are also compared for the suggested repowering plants.

INTRODUCTION

Due to the ever-increasing demand for more efficient power production and distribution, the main topics of research and development in the field of electricity production are improving efficiency and reducing pollutant emissions. Converting existing steam power plant into combined cycle (CC) is though known as repowering. It would be ideal for an old steam plant in which steam turbine after many years of operation still has considerable service life expectancy but for example the boiler is ready to be replaced. The boilers are normally replaced or supplemented with gas turbines and heat recovery steam generators (HRSG) see e.g. (Kehlhofer et al. 2009). Thus there is an increased interest in developing an old coal fired steam plants into a CC plant and increase their power output and efficiency, and at the same time decrease their emissions, see e.g. (Termuehlen 1994), (Kovacik and Stoll, 1990).

Currently repowering of steam plants can be achieved in two ways; feed water repowering and boiler repowering, see e.g. (Carapellucci and Milazzo, 2006). The first option uses heat from the turbine exhaust to raise the feed water temperature instead of bleeding steam. This means that increased steam flow has to be managed by the low pressure section of the original steam turbine, requiring either extensive modification of the steam turbine or impairing the repowered plant performance. The other option, boiler repowering, entails major steam generator redesign or replacement. Gas turbine exhaust gas is used as heat source for the existing steam cycle. This increases plant efficiency close to that of new combined cycle plants. Such repowering has been performed on various old steam plants, see e.g. (Chellini, 1986), (Donatelli, 1990), (Walter et al., 1996). The second option is widely used across developed countries in which many steam plants are relatively old and are coal fired, which is also used in this study.

Steam turbine units in older power stations generally have relatively low steam data and can easily be adapted for use in combined cycles as bottoming cycle for a gas turbine (gas turbines). Depending on the steam plant data such as live steam temperature, pressure and mass flow, one needs to screen available gas turbines in the market and choose one which can easily be adapted in the basic steam plant without changing its original configurations. If one gas turbine cannot supply the required heat and temperature then one may complement the repowering with a supplementary firing or two gas turbines. In this study both options will be used.

In this study it is also suggested to use a third option which is repowering with SOFC. Solid oxide fuel cell (SOFC) stacks will soon enter the commercialization phase and therefore it would be interesting to integrate such technology into repowering of old steam plants.

SOFCS are one of the most promising types of fuel cells, particularly regarding energy production. They are expected to produce clean electrical energy at high conversion rates with low noise and low pollutant emissions (Calise et al., 2006). The exhaust temperatures of SOFCs are high due to the high operating temperature of the cells. Additionally, because the fuel utilization in the fuel cell is less than 100 percent, the unreacted fuel needs to be combusted in a burner. This combustion in turn produces even hotter off-gases that are perfectly suited for use in a steam generator to produce steam for the bottoming steam cycle.

Numerous studies have investigated SOFC-based power systems and suggested high thermal efficiencies in the literature. However, the majority of these studies use gas turbines as the bottoming cycle, see, e.g., (US Department of energy, 2004), (Riensche et al., 2000) and (Haseli et al. 2008). A steam turbine has also been used as a bottoming cycle (Rokni 2010a and Rokni 2010b), resulting in high plant efficiency. At present, using the Brayton and Rankine

cycles as bottoming cycles for SOFC seems to be the most practical because of the maturity of these technologies. Given that the development trends suggest that the operating temperature of the SOFC will decrease, using gas turbine as bottoming cycle will become less beneficial over time.

The present work is an analytical study that conducts a thermodynamic investigation of repowering of old steam plants with SOFC that also functions as a topping cycle for a steam plant using the heat from the off-gasses exhausted from the topping cycle. The results will be compared with the traditional repowering strategies using gas turbine as the driving heat. One gas turbine with supplementary firing, two gas turbines as well as two gas turbines with supplementary firing will be used. The comparison will be studied in terms of plant thermal efficiency and CO₂ emission. The SOFC is based on a theoretical model with empirical coefficients calibrated from experimental data.

No investigation on steam plants repowering with SOFC has been found in the open literature, and therefore, the current investigation seems to be completely novel and might bring up new ideas on designing new energy system configurations for future applications. It should also be noted that the system presented here was studied thermodynamically and that the objective of this study was not to present or discuss the associated costs. The performances of the various plants are compared in terms of efficiency, fuel consumption and other related parameters.

ORIGINAL PLANT MODEL

The principal components of the plant are the burner, steam generator, high pressure turbine (HP), two intermediate pressure turbines (IP), low pressure turbine (LP), condenser and deaerator. The coal burner provides the heat needed for generating steam in a single pressure level steam generator through economizer (Eco), evaporator (Eva) and super heater (SH). Three steam extractions from the steam turbines are used to preheat (PH) the sub-cooled water after the condenser. Coal is supplied at point 61 in the figure while ash is removed from the burner at point 62 in the figure. The coal composition (mass based) is assumed to be 0.7818 C (solid form), 0.0489 H₂, 0.0603 O₂, 0.0171 N₂, 0.0102 S (solid form) and 0.0817 water (liquid form). The net calorific and gross caloric values are 31120 kJ/kg and 32380 kJ/kg, respectively, with a mean mole mass of 10.34 kg.

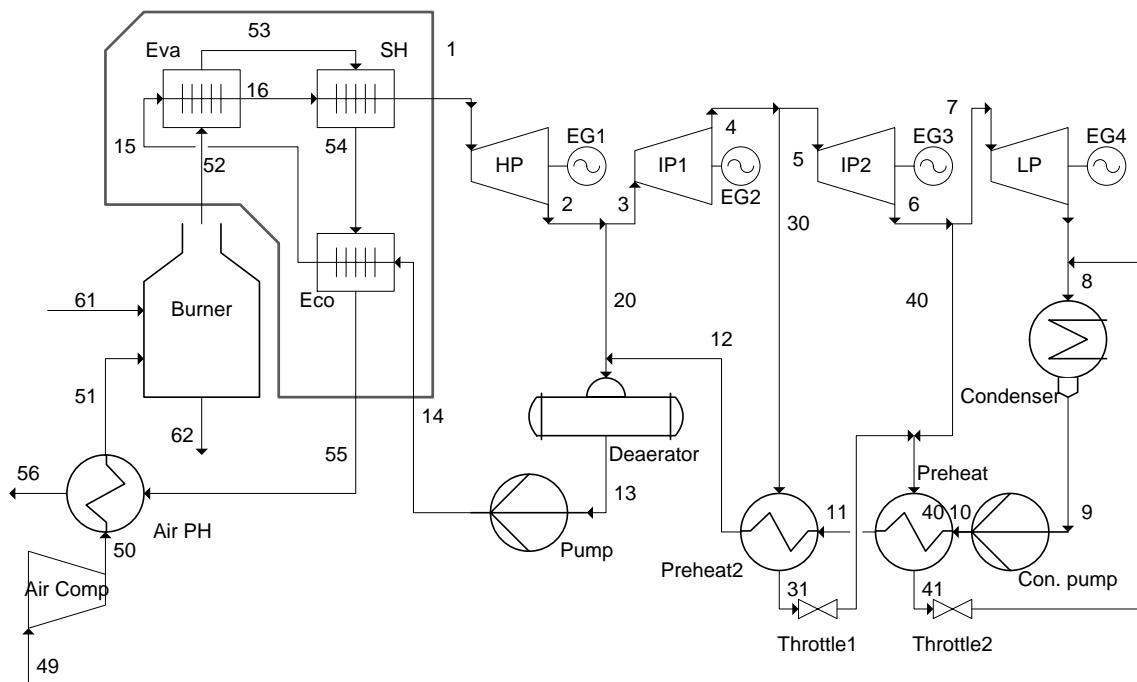


Figure 1. Kyndby original coal steam plant.

The plant net output power is 264MW with an efficiency of about 33% (LHV). Live steam temperature, pressure and mass flow (point 1 in the figure) is 500°C, 80 bar and 280 kg/s, respectively. The power required to generate such steam is about 756.168 MW, which can be calculated from enthalpy difference between economizer inlet and super heater outlet (live steam) multiplying with mass flow rate. This of course is lower than coal power input due to losses through air preheating and air compressor for the boiler. Main parameters for the turbines are summarized in Table 1.

Table 1. Turbines parameters.

Turbine	Isentropic efficiency	Turbine constant
High pressure turbine	0.885	97.75
Intermediate pressure turbine 1	0.878	766.3
Intermediate pressure turbine 2	0.811	2467
Low pressure turbine	0.7565	11140

Turbine constant is a parameter that depends on the turbine mass flow, the inlet temperature as well as inlet and outlet pressure defined as,

$$C_T = \frac{\dot{m}\sqrt{T}}{\sqrt{p_{in}^2 - p_{out}^2}} \quad (1)$$

Ambient conditions are assumed to be 25°C and 1.01 bar, both for air (point 49 in Fig. 1) and coal (point 61 in Fig. 1). Other important data are shown in Table 2.

Table 2. The main plant parameters.

Parameter	Value	Node in Fig.1
Coal		61
Fuel consumption (mass flow), (kg/s)	25.75	
Fuel consumption (mass flow), (MW)	801.146	
Burner	600	
Air fuel ration, λ	1,2	
Exhaust		56
Temperatures (°C)	140	
Pressure (bar)	1.01	
Other conditions		
Maximum pressure, (bar)	100	14
Minimum pressure, (bar)	0.081	9
Others		
Air preheater effectiveness, (%)	80	
Generators efficiency, (%)	97	
Power output, (MW)	263.932	
Plant efficiency based on LHV, (%)	32.94	

MODELLING

The modeling for SOFC and gas turbine will be briefly explained below while modeling of other components will be referred to previous publications.

SOFC Modeling

The SOFC model developed in (Bang-Møller and Rokni, 2010) is used in this investigation, which were calibrated against experimental data for planar SOFC type. For the sake of clarity, it is shortly described here. In such modeling one must distinguish between electrochemical modeling, calculation of cell irreversibility (cell voltage efficiency) and the species compositions at outlet. For electrochemical modeling, the operational voltage (E_{cell}) was found to be

$$E_{cell} = E_{Nernst} - \Delta E_{act} - \Delta E_{ohm} - \Delta E_{conc} \quad (2)$$

where E_{Nernst} , ΔE_{act} , ΔE_{ohm} and ΔE_{conc} are the Nernst ideal reversible voltage, activation polarization, ohmic polarization and concentration polarization. Assuming that only hydrogen is electrochemically converted, then the Nernst equation can be written as

$$E_{Nernst} = \frac{-\Delta g_f^0}{n_e F} + \frac{RT}{n_e F} \ln \left(\frac{p_{H_2, tot} \sqrt{p_{O_2}}}{p_{H_2O}} \right) \quad (3)$$

$$p_{H_2, tot} = p_{H_2} + p_{CO} + 4p_{CH_4} \quad (4)$$

where Δg_f^0 is the Gibbs free energy (for H_2 reaction) at standard pressure. The water-gas shift reaction is very fast and therefore the assumption of hydrogen as only species to be electrochemically converted is justified, see (Holtappels et al., 1999) and (Matsuzaki and Yasuda, 2000). In the above equations p_{H_2} and p_{H_2O} are the partial pressures for H_2 and H_2O respectively.

The activation polarization can be evaluated from the Butler–Volmer equation (Keegan et al., 2002), which is isolated from other polarizations to determine the charge transfer coefficients and exchange current density from the experiment by the curve fitting technique.

The ohmic polarization (Zhu and Kee, 2003) depends on the electrical conductivity of the electrodes as well as the ionic conductivity of the electrolyte. This was also calibrated against experimental data for a cell with anode thickness, electrolyte thickness and cathode thickness of 600 μm , 50 μm and 10 μm respectively.

The concentration polarization is dominant at high current densities for anode-supported SOFCs, wherein insufficient amounts of reactants are transported to the electrodes and the voltage is then reduced significantly. Again the concentration polarization was calibrated against experimental data by introducing the anode limiting current, (Costamagna et al., 2004), in which the anode porosity and tortuosity were also included among other parameters.

The fuel composition at anode outlet was calculated using the Gibbs minimization method as described in (Smith et al., 2005). Equilibrium at the anode outlet temperature and pressure was assumed for the following species: H_2 ,

CO, CO₂, H₂O, CH₄ and N₂. Thus the Gibbs minimization method calculates the compositions of these species at outlet by minimizing their Gibbs energy. The equilibrium assumption is fair because the methane content in this study is very low.

To calculate the voltage efficiency of the SOFC cells, the power production from the SOFC (P_{SOFC}) depends on the amount of chemical energy fed to the anode, the reversible efficiency (η_{rev}), the voltage efficiency (η_v) and the fuel utilization factor (U_F). It is defined in mathematical form as

$$P_{SOFC} = (\text{LHV}_{H_2} \dot{n}_{H_2,in} + \text{LHV}_{CO} \dot{n}_{CO,in} + \text{LHV}_{CH_4} \dot{n}_{CH_4,in}) \eta_{rev} \eta_v U_F \quad (5)$$

where U_F was a set value and η_v was defined as

$$\eta_v = \frac{\Delta E_{cell}}{E_{Nernst}} \quad (6)$$

The reversible efficiency is the maximum possible efficiency defined as the relationship between the maximum electrical energy available (change in Gibbs free energy) and the fuels LHV (lower heating value) as follows, (see e.g. Winnick, 1997)

$$\eta_{rev} = \frac{(\Delta \bar{g}_f)_{fuel}}{\text{LHV}_{fuel}} \quad (7)$$

Additionally, equations for conservation of mass (with molar flows), conservation of energy and conservation of momentum were also included into the model. Table 3 displays the main parameters for the SOFC stacks used in this study.

Table 3. The main SOFC parameters used in this study.

Parameter	Value
Fuel utilization factor	0.8
Current density, (mA/cm ²)	300
Cathode pressure drop ratio (bar)	0.1
Anode pressure drop ratio (bar)	0.05
Cathode inlet temperature (°C)	600
Anode inlet temperature (°C)	650
Outlet temperatures (°C)	780
DC /AC converter efficiency	0.97

Modeling of Other Components

Modeling of other components such as heat exchangers, pumps, desulfurization reactor, etc. are adopted from the study of (Rokni, 2013a), in which the reliability of the components modeling was justified by building a benchmark system consisting SOFC, methanator, heat exchanger, etc. and fed with different fuels such as natural gas, ethanol, methanol and di-methyl ether (DME). The obtained results agreed well with the corresponding data obtained by other researchers in the open literature for all cases studied.

Modeling of Selected Gas Turbine

In (Gas turbine world, 2007) the specification of all gas turbines currently available in the market is specified. All gas turbines in the data sheet are screened and based on the required temperature as well as heat for the steam cycle, the gas turbine chosen here is Siemens SGT5 4000F. The specifications in the specs 2007 are slightly different from the one in Siemens website, which could depend on improvement. Therefore, an average data is chosen which is summarized in Table 4. A gas turbine model based on these data is then developed here to capture all important specifications such as power output, efficiency, etc.

Table 4. Comparison between Siemens SGT5 4000F and the model developed here.

Parameter	Datasheet value	Model	Error (%)
ISO base rating, (MW)	288	290.95	1.0
Heat rate, (kWh)	9114	9111.4	0.0
Efficiency LHV, (%)	39.5	39.5	0.0
Pressure ratio	18	18	–
Exhaust mass flow rate, (kg/s)	688	688	–
Turbine speed, (rpm)	3000	–	–
Exhaust temperature, (°C)	580	580.0	–

As seen in the exhaust gas temperature if this gas turbine is well above live steam temperature of 500°C, allowing for a large terminal temperature and consequently lower HRSG cost. In fact that the exhaust temperature of the gas turbine must be above 500°C, eliminates the choice of many gas turbines listed in the screening process.

As mentioned above, the minimum power (heat) required for the steam plant is about 756 MW. From the gas turbine specifications one can calculate its exhaust power by

$$Q_{\text{exhaustGT}} = Q_{\text{in,GT}} - P_{\text{GT}} = P_{\text{GT}} \left(\frac{1}{\eta_{\text{GT}}} - 1 \right) \quad (8)$$

which gives about 441 MW. This in turn means that one gas turbine alone will not be enough to generate the required steam and supplementary firing will be necessary. Another option would be using two gas turbines either without supplementary firing or including supplementary firing.

In modeling ambient temperature and pressure are assumed to be 25°C and 1.01 bar, respectively. Generator efficiency is assumed to be 97% which is typical value. The calculated fuel mass flow and fuel consumption (based on LHV) are 16.08 kg/s respective 736.7 MW.

The turbine inlet temperature set in the model does not correspond to the inlet temperature of the real gas turbine. In reality, during the expansion both gases and air cooling are mixed and results in a lower average temperature. However, in modeling cooling air is neglected and therefore the inlet temperature would be higher than the reality. Thermodynamically, the most important parameters would be gas turbine exhaust temperature, exhaust mass flow, fuel consumption, power production and efficiency which all are calculated correctly.

SUGGESTED REPOWERING CONFIGURATIONS

As mentioned above, the idea is to maintain the steam cycle as it is and replace the burner with a HRSG. Adding a gas turbine (or gas turbines) on the top of the steam and designing CC is not new but will be studied here for comparison with the new suggested plant.

Combined Cycles

The first option for CC plant is to use one GT with supplementary firing as shown in Fig. 2. In the configuration, the HRSG is designed with one drum connected to the evaporator. The off-gases are sent out at point 55 in the figure. The components settings are not changed for the steam plant at all, allowing less cost associated for repowering.

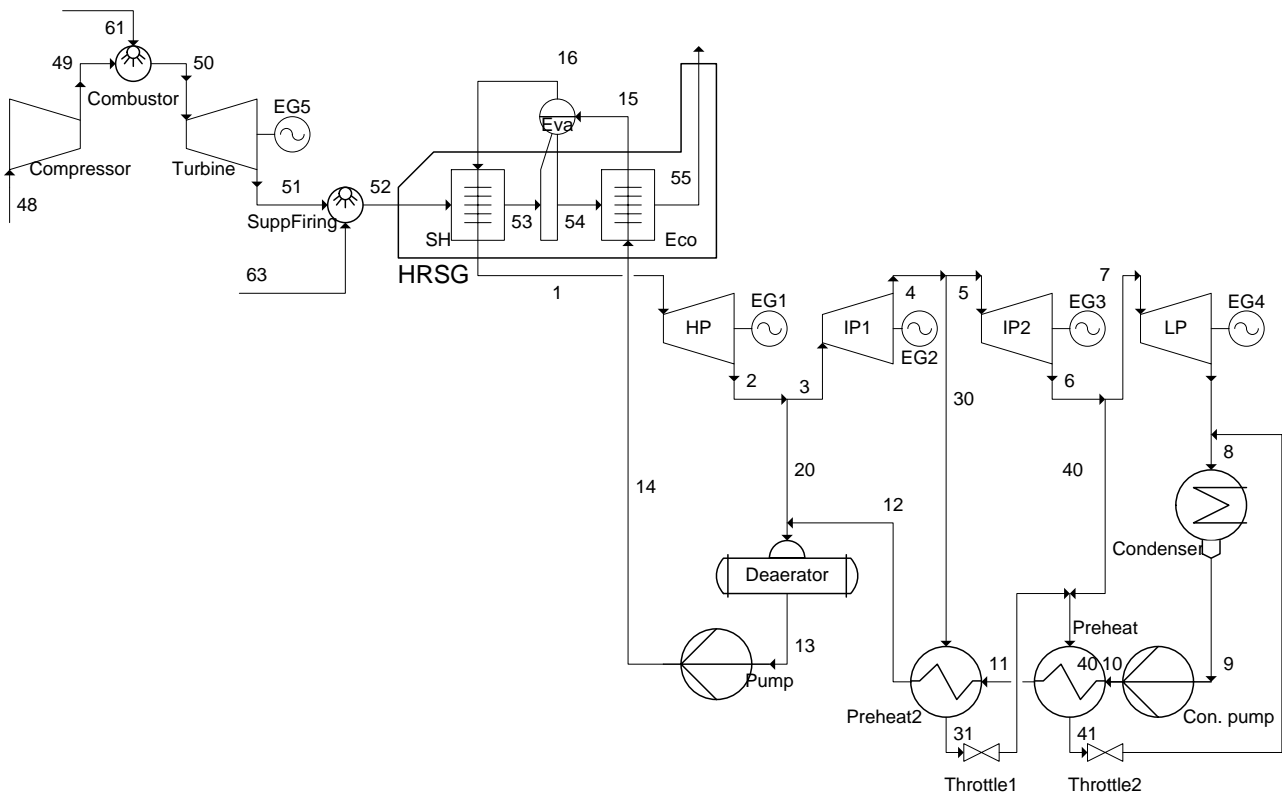


Figure 2. Natural gas fired CC plant with one GT and supplementary firing.

As shown in the figure, the fuel (NG) shall be supplied to the gas turbine chamber at point 61 as well as supplementary firing at point 63. With the estimations shown above the minimum power required from the supplementary firing will be about 315 MW, which in turn requires a large size burner as supplementary firing. Another option is to have two gas turbines with or without supplementary firing as displayed in Fig. 3. Generally, including a supplementary firing has the pros for allowing shutting down one gas turbine to undergo service without shutting down the entire plant. In this configuration, fuel is only supplied to the gas turbines' combustion chambers at points 61 and 62, if no supplementary firing is used. By including supplementary firing then fuel must be supplied to point 63 in addition to the gas turbines combustion chambers (points 61 and 62 in the figure). The HRSG design is similar to

case with one gas turbine, allowing for fair thermodynamic comparison. It should be noted that in the case with two gas turbines the repowering cost is substantially higher than the corresponding case with one gas turbine.

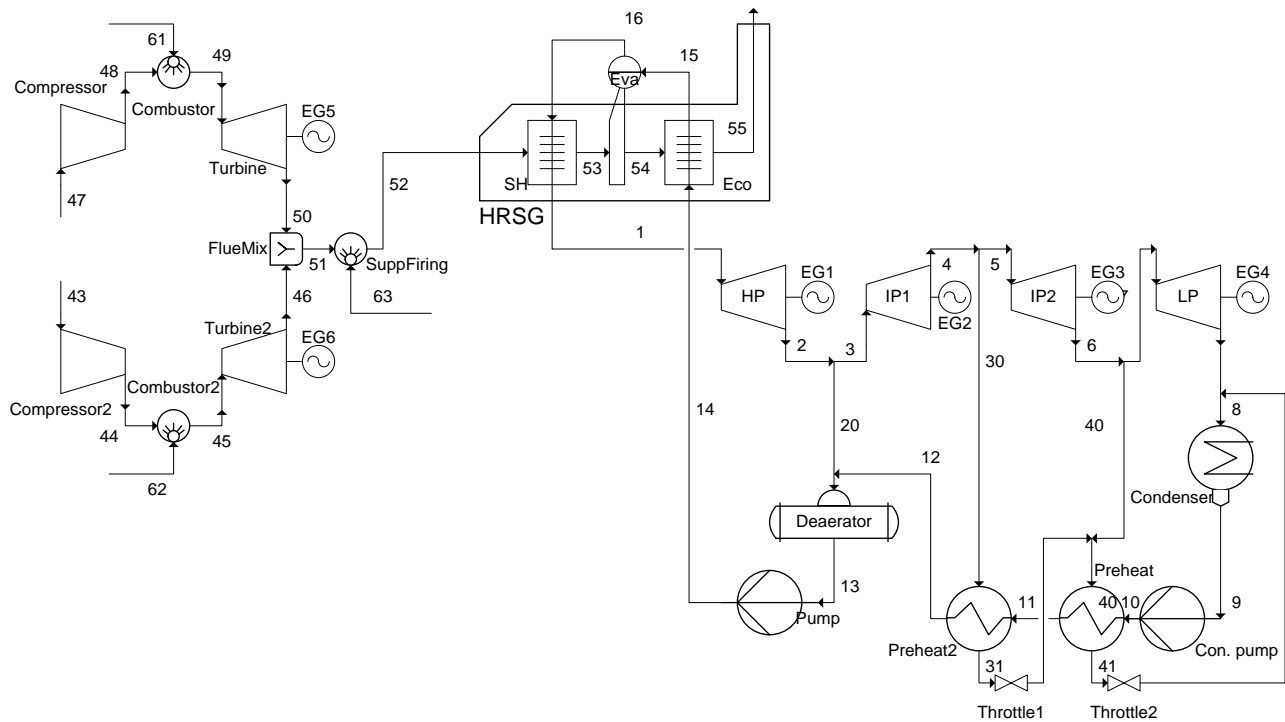


Figure 3. Natural gas fired CC plant with two gas turbines and with or without supplementary firing.

New Hybrid Cycle

The new system suggested here for repowering is presented in Fig. 4, which uses a natural gas fired SOFC system functioning as a topping cycle, while the steam cycle comprises the bottoming cycle.

For the topping SOFC cycle, the ambient air at 25°C is compressed to the working pressure of the SOFC (normal pressure) and then heated in the cathode air preheater (Cathode PH in the figure) to 600°C before entering the cathode side of the SOFC stacks. For the anode side, the fuel was preheated in a heat exchanger (NG PH in the figure) before it was sent to a desulfurization unit to remove the sulfur content in the NG. This unit was assumed to be using a catalyst and operated at temperature of 200°C. The heavier carbon contents in the desulfurized gas are cracked down in a CPO (Catalytic Partial Oxidation) type pre-reformer. Before that, the fuel must be preheated again to reach the operational temperature of the CPO catalyst, which is accomplished in the reformer preheater (Ref PH in the figure). The temperature of the pre-reformed gas is supposed to reach 650°C which is high enough to be sent to the anode side of the SOFC. The off-fuel out of the fuel cell is used to preheat the fuel during its paths. The operating temperature of the fuel cell is assumed to be 780°C which is enough to preheat the incoming gas. The entering temperatures mentioned above are the minimum entering temperatures and are essential requirements for the proper functioning of SOFC stacks, not only to initiate the chemical reactions but also to avoid cell thermal fractures. The burner is implemented because all of the fuel will not be reacted in the fuel cell stacks due to SOFC fuel utilization factor.

The off-gases from the burner have a high heat quality, which can be used to generate steam in a HRSG through economizer, evaporator and super heater. As discussed in (Rokni, 2010a) and (Rokni, 2012), the off-gases out of HRSG maintains a high quality heat, which can be used to preheat the air after the compressor in the SOFC cycle. In other words, heat is recycled back to the topping cycle, and therefore, this technique is called hybrid recuperation. Such hybrid recuperator (HR) is shown to be very efficient and can increase the plant efficiency significantly. It increases the energy supplied to the SOFC cycle which in turn decreases the duty of the cathode pre-heater. Therefore, the energy from the SOFC off-fuel will be higher, allowing for more heat to be available after the burner. Other parameters assumed for the SOFC plant are summarized in Table 5.

Table 5. System operating input parameters.

Air compressor isentropic efficiency	0.8
Air compressor mechanical efficiency	0.95
Heat exchangers air side pressure drops, (bar)	0.08
Hybrid recuperator gas side pressure drop, (bar)	0.1
Hybrid recuperator effectiveness	0.9
Heat exchangers fuel side pressure drops, (bar)	0.05
Reformer compressor isentropic efficiency	0.85
Reformer compressor mechanical efficiency	0.95
Desulfurizer pressure drop, (bar)	0.05

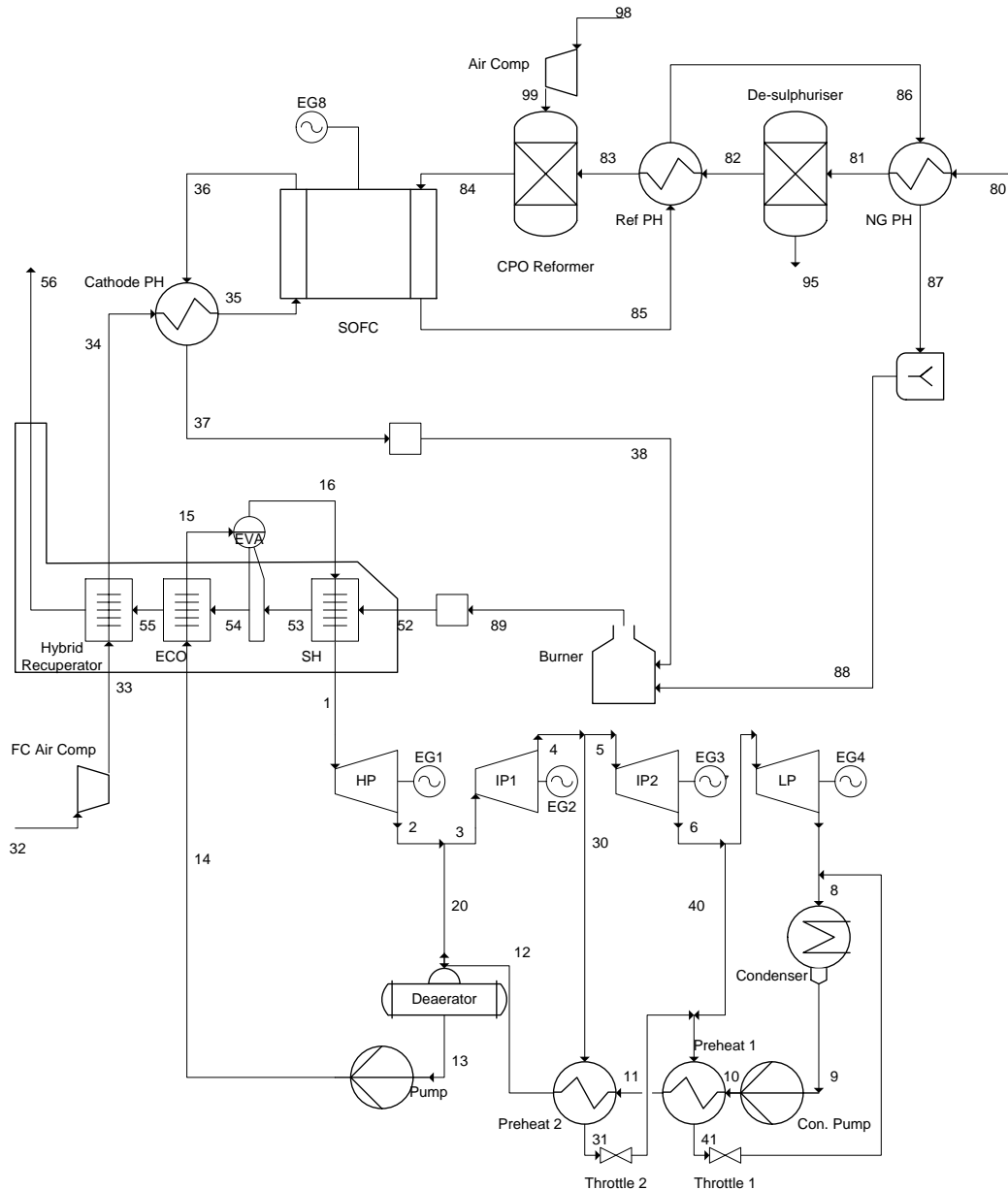


Figure 4. Natural gas fired SOFC – steam hybrid plant.

RESULTS AND CONCLUSIONS

Natural gas is assumed to be pressurized and have the following compositions; $\text{CH}_4 = 0.87$, $\text{C}_2\text{H}_6 = 0.081$, $\text{C}_3\text{H}_8 = 0.01$, $\text{C}_4\text{H}_{10}\text{-N} = 0.006$, $\text{CO}_2 = 0.02925$, $\text{H}_2\text{S} = 0.00375$.

The calculations show that the heat required from the steam cycle is not enough to use of two gas turbines without supplementary firing. The exhaust gases out of the gas turbines are mixed but the total heat provided in the exhausts is still not enough to satisfy the request from the steam cycle and small amount of supplementary firing is in fact needed. Due to the high excess air in the gas turbines, the oxygen necessary for the supplementary firing is already bounded in the off gases. Since two gas turbines are able to provide more than 90% of the heat needed by the steam cycle, then it is possible to modify the topping cycle in order to avoid the use of supplementary firing. This can be done by increasing the turbine outlet temperature (TOT) and therefore, in the calculations such option is also included. Higher gas turbine outlet temperature can be achieved by decreasing the efficiency of the turbine. A simple energy balance shows that the turbine outlet temperature must be about 671°C so that the gas turbines can provide the required heat demand for the steam cycle. Adding 1°C margin then, 672°C can be chosen as the optimum turbine outlet temperature. Thus, the calculations for the CC with 2 gas turbines but without supplementary firing are carried out with outlet temperature of 672°C .

The performance comparison among repowering plants presented above is shown in Fig. 5, in terms of plant net power output. As can be seen, already with one gas turbine and supplementary (CC - 1 GT + SF in the figure) firing the net power can be increased by more than 210% compared to the base case (original steam plant). Adding 2 gas turbines without supplementary firing (CC - 2 GT in the figure) increases the net power by about 270% while including a supplementary firing (CC - 2 GT + SF in the figure) further increases the net power by additional 50% (320% in total). So far, all such repowering lies within the CC plants category. The suggested

repowering with SOFC without supplementary firing (SOFC in the figure) increases the net power more than 375% (almost 4 times larger). Thus the suggested hybrid SOFC–ST plant performs far better than the CC plants.

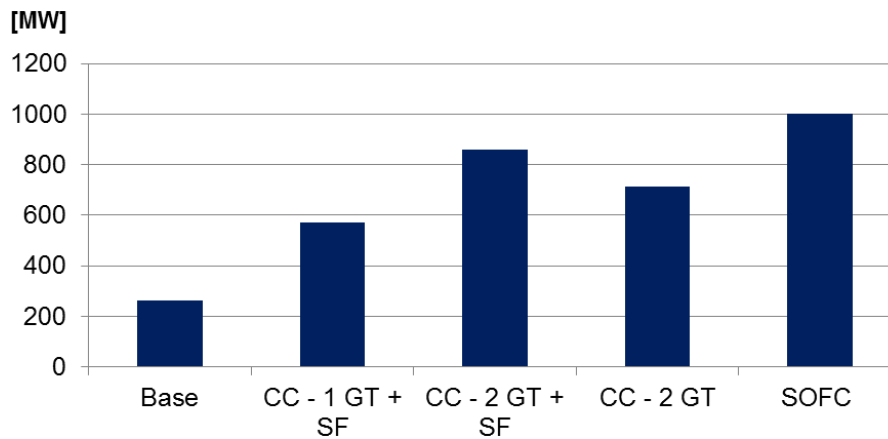


Figure 5. Comparison performance of the repowering plants in terms of power.

Another interesting performance comparison could be plant thermal efficiency and CO₂ emissions. These are displayed in Fig. 6. As demonstrated in the figure, among CC category, repowering with 2 gas turbines and supplementary firing has the best efficiency which is about 53%. This is of course lower than a new designed CC plant which reaches to about 59%. The reason is that the steam plant is not designed for the gas turbines but instead the gas turbines are fitted with an existing steam plant. The CC - 1 GT + SF (CC plant with 1 gas turbine with supplementary firing) as well as CC - 2GT (CC plant with gas turbines without supplementary firing) cannot achieve 50% plant efficiency. However, repowering with SOFC results in plant efficiency more than 60% and can compete with a new designed CC plant. Again, the efficiency of repowering with SOFC is well below a new designed SOFC-ST (cf. Rokni, 2010a).

Here, the specific CO₂ emission is defined as

$$e_{CO_2} = \frac{\dot{m}_{CO_2}}{P_{el}} \quad [\text{kg}_{CO_2}/\text{kWh}_{el}] \quad (9)$$

which is the mass flow of CO₂ per net power output (electricity). As seen in Fig. 6, the specific emission of CO₂ for the base case (coal fired steam plant) is about 1.01 kg/kWh. The results clearly demonstrate that the higher the efficiency is the lower CO₂ emission will be. For the CC category the combined cycle with two gas turbines and supplementary firing (CC - 2GT + SF) has the lowest CO₂ emission which is about 0.39 kg/kWh which is only about 40% of the original plant. This of course is much lower than base case, but all the decrease is not only due to plant efficiency but also because the fuel is changed from coal to natural gas. Therefore, another case is included in the figure which is steam plant fired with natural gas instead of coal (NG SC in the figure). Natural gas fired steam plant has an emission that is about 60% of the coal fired plant.

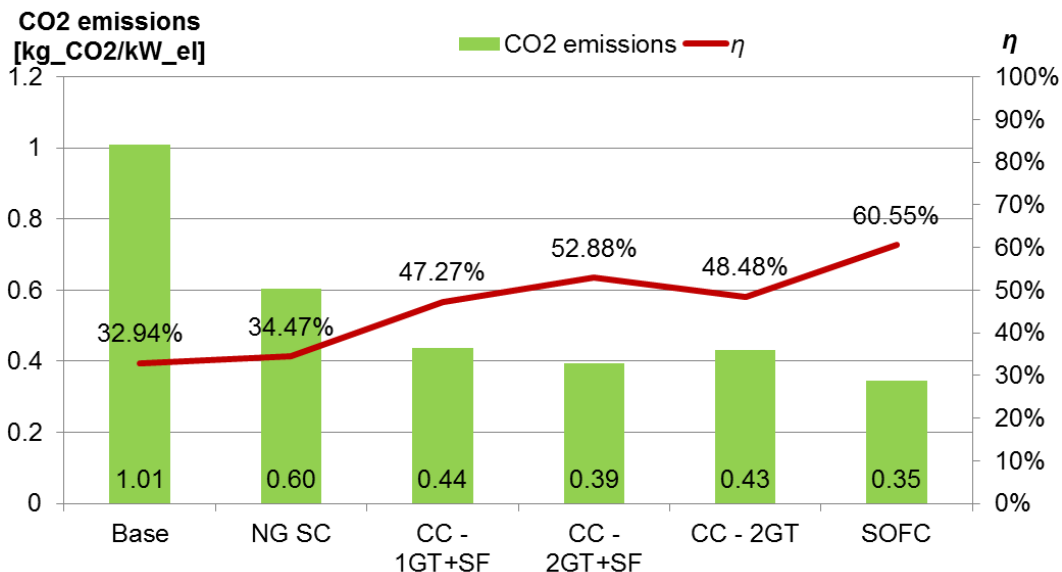


Figure 6. Comparison performance of the repowering plants in terms of plant thermal efficiency and CO₂ emission.

The suggested repowering with SOFC plant performs best with an emission of about 35% compared to the original plant, but also about 60% of the original plant fired when natural gas instead.

Other plants calculated data are shown in Table 6, in terms of fuel consumption, total fuel rate, auxiliary power and supplementary fuel mass flow. As can be seen the auxiliary power consumption for CC category plants are much higher which is due to compressor of the gas turbines. The auxiliary power consumption for the presented SOFC plant is relatively very low compared to the CC plants, which is due to the non-pressurized SOFC stacks. Supplementary fuel consumption for the CC plant with 2 GT and with supplementary firing is only 3.34 kg/s which is very low, explaining that the two gas turbines can generate about 90% of the heat required by the original steam plant.

Table 6. Plant performance for different configurations.

Parameter/Configuration	Base	CC - 1GT + SF	CC - 2GT	CC - 2GT + SF	SOFC
Fuel consumption, (kW)	801.147	1191.346	1473.322	1626.379	1655.807
Total fuel flow rate, (kW)	25.75	26	32.16	35.5	36.14
Auxiliary power, (kW)	17.639	297.254	590.993	590.993	118.014
Supplementary fuel rate, (kg/s)	–	9.92	–	3.34	–

T – Q Diagram

To study the reason why the presented repowering with SOFC (SOFC – ST hybrid) is superior on CC plants in terms of plant efficiency, one need to analyze the temperature–heat diagram for HRSG among others. Such diagram for repowering with SOFC is shown in Fig. 7, in which the temperature and heat of each components in the HRSG is shown with corresponding node number appear in Fig. 4. For all case the pinch temperature (difference between nodes 54 and 15) is set to 10°C. The terminal temperature difference (difference between node numbers 52 and 1) is about 93°C and the gases leave the HRSG at temperature about 113°C. Significant energy has been recovered by hybrid recuperation, from 218°C to 113°C, which corresponds to 20% of total energy recovered in the HRSG. As also seen, both the super heater and economizer uptakes each 20% of the total energy recovered by HRSG. About 40% of the total energy in the HRSG is allocated by evaporator.

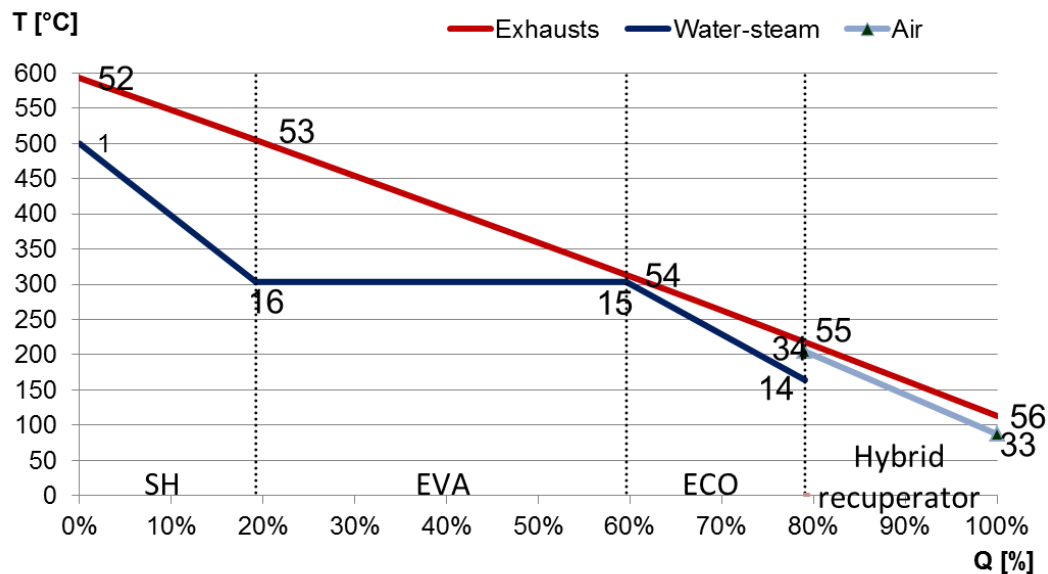


Figure 7. The heat - temperature diagram for HRSG of the SOFC – ST hybrid system.

Similar temperature–heat diagram is shown for the combined cycle with 2 gas turbines and with supplementary firing. The reason that CC - 2GT + SF is chosen is that this combined cycle performs best among all combined cycles studied here. The gases leave the HRSG at a temperature of about 164°C which is significantly higher than the case with SOFC repowering. Thus lower energy has been recovered in HRSG for the CC case compared with SOFC case. The terminal temperature is about 165°C which is also higher in this case when compared with previous case. Here both super heater and economizer uptake each about 25% of the energy in the HRSG, which is slightly higher than the SOFC case. Evaporator absorbs about 50% of the energy from HRSG, which is also higher when compared with SOFC repowering. All these together make the area between the off-gases temperature line (red line) and the water-steam temperature line (blue line) to be larger than the case with SOFC repowering. This in turn means that less exergy has been wasted in HRSG when SOFC repowering is used. In other word, for the case with SOFC repowering, the off-gases temperature line approaches the corresponding line for water-steam and therefore resulting in less exergy loss and higher effectiveness loss for HRSG. The effectiveness of HRSG can be defined as (see e.g. Rokni, 2012);

$$\varepsilon_{HRSG} = \frac{T_{gas,in} - T_{gas,out}}{T_{gas,in} - T_{ambient}} \quad (10)$$

then the HRSG effectiveness can be calculated as 78.4% and 84.5% for the CC - GT + SF combined cycle respective SOFC - ST hybrid system.

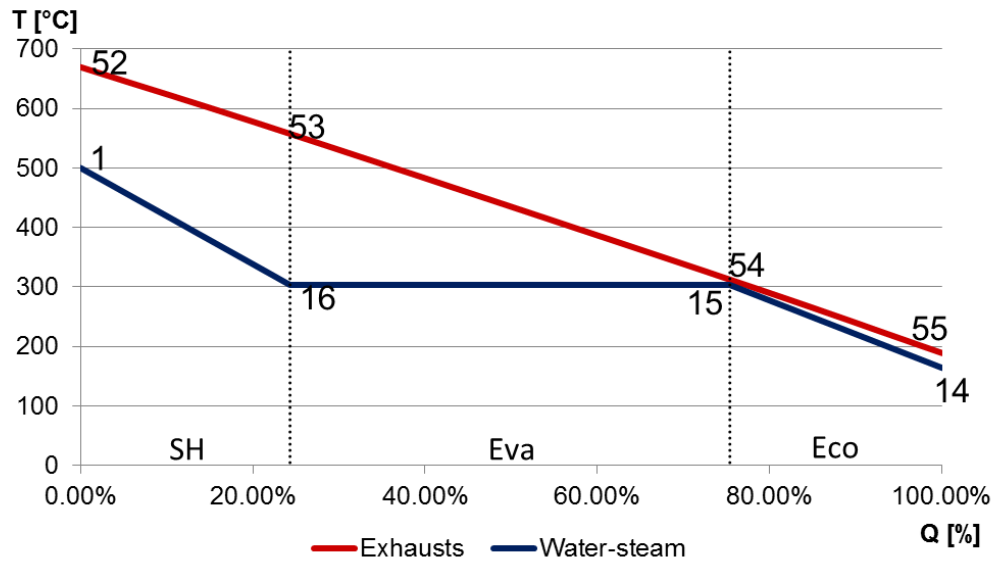


Figure 8. The heat - temperature diagram for HRSG of the CC - 2G + SF combined cycle.

Effect of SOFC Current Density and Operating Temperature

As discussed in (Rokni, 2012), increasing SOFC current density decreases plant efficiency, while increasing SOFC operating temperature is in favor for plant efficiency. Similar study can also be carried out here, which is presented in Fig. 9. Generally, increasing SOFC current density decreases power generated by SOFC and thereby decreases plant efficiency as well. This is of course also true for SOFC powering, see Fig 9a. Decreasing current density below 100 mA/cm² will not be realistic since the cell voltage reaches to a very high value, 0.9374V, close to open circuit voltage. At this current density plant efficiency reaches to 67.4% which is significantly higher than the corresponding efficiency at 300 mA/cm².

On the other hand, increased SOFC operating temperature is not always in favor for plant efficiency as established in Fig. 9b. In fact, there exists an optimum operating temperature at which the plant efficiency is maxima, which is in contrast with the study of (Rokni, 2012). Note that in the study of (Rokni, 2012) steam plant is designed based on the SOFC topping cycle while here the topping SOFC cycle is designed to provide required heat for the existing steam plant. This maximum efficiency is calculated to be about 62% at temperature of 740°C, when current density is set to 300 mA/cm². This temperature is lower than the current temperature technology of 780°C, which in turn means companies' endeavor to decrease the SOFC operating temperature, is in favor for such repowering system if this is decreased slightly.

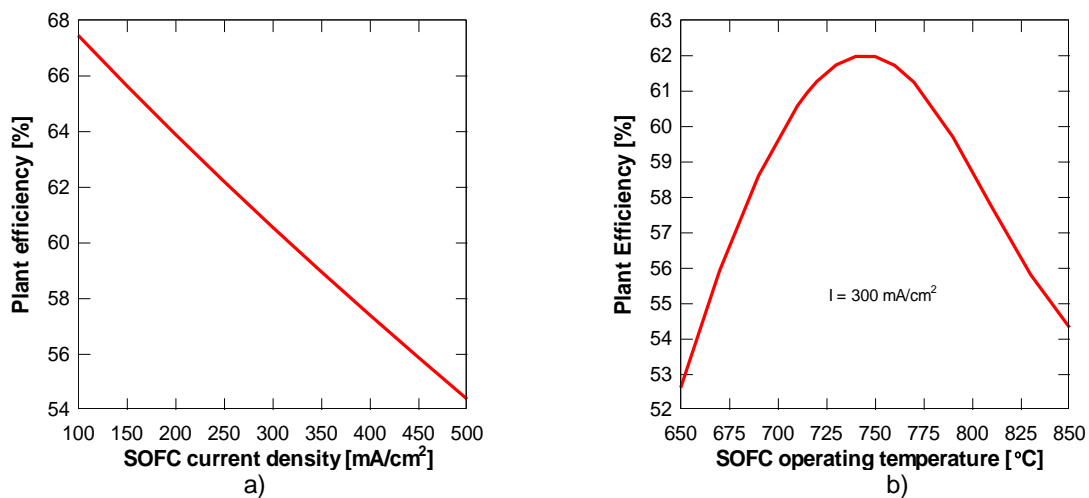


Figure 9. Effect of SOFC current density (a) and operating temperature (b) on plant efficiency of repowering with SOFC.

CONCLUSIONS

Repowering of an existing coal fired power plant is studied and different repowering design is analyzed. In addition, a new repowering with SOFC plant is also suggested. CO₂ emission from different plant design are calculated and compared with each other. The following conclusions can be drawn;

- Repowering with SOFC produces the highest power
- Repowering with SOFC have the highest plant efficiency which is about 60% and competes with a new CC plant in terms of efficiency
- CO₂ emission from the SOFC repowered plant is far less than the original coal fired plant but also much lower than if the original plant was powered with natural gas instead of coal.
- Among CC plants, the combined cycle with two Siemens SGT5 4000F gas turbines with small supplementary firing has the best performance with an efficiency of 53% which is considerably lower than a new designed CC plant.
- It is possible to use two Siemens SGT5 4000F gas turbines without supplementary firing if gas turbines outlet temperature is increased by reducing expander efficiency.
- There exists an optimum SOFC operating temperature at which plant efficiency is maxima. This temperature is calculated to be 740°C for 300 mA/cm².
- It is possible to reach plant efficiencies above 65% if current density is low enough.

NOMENCLATURE

c_p	Specific heat, J/kg°C
C_T	Turbine constant
E	Voltage, V
F	Faradays constant, C/mol
e	emission, kg/kWh
g^0	Standard Gibbs free energy, J/mol
g_f	Gibbs free energy, J/mol
\dot{m}	Mass flow, kg/s
\dot{n}	Molar reaction rate, mol/s
n_e	Number of electron
P	Power, W
p	pressure, bar
T	Operating temperature, K
Q	Heat, J
R	Universal gas constant, J/mol K
U_F	Fuel utilization factor

Greek Letters

Δ	difference
η	efficiency

Subscripts

act	activation
conc	concentration
ohm	ohmic
rev	reversible
v	voltage

Abbreviations

AP	Anode pre-heater
CC	Combined cycle
CPO	Catalytic partial oxidation
CP	Cathode air pre-heater
EG	Electric generator
Eco	Economizer
Eva	Evaporator
FC	Fuel cell
GT	Gas turbine
HHV	Higher heating value
HP	High pressure
HR	Hybrid recuperator
HRSG	Heat recovery steam generator
IP	Intermediate pressure
LHV	Lower heating value
LP	Low pressure
NG	Natural gas
PH	Preheater

SH Super heater
SOFC Solid oxide fuel cell

REFERENCES

- [1] Bang-Møller C. and Rokni M. 2010. Thermodynamic performance study on biomass gasification, solid oxide fuel cell and micro gas turbine hybrid systems. *Energy Conversion and Management* 51(12):2330–39.
- [2] Calise F., Dentice d'Accadia M., Palombo A. and Vanoli L. 2006. Simulation and exergy analysis of a hybrid solid oxide fuel cell (SOFC)–Gas turbine system. *Energy* 31:3278–99.
- [3] Carapellucci R. and Milazzo A. 2006. Repowering combined cycle power plants by a modified STIG configuration. *Energy Conversion and Management* 48(5):1590–1600.
- [4] Chellini, 1986. Repowering a steam power plant with a gas turbine. *Diesel and Gas Turbine Worldwide* 18(8):28–30.
- [5] Costamagna P., Selimovic A., Del Borghi M. and Agnew G. 2004. Electrochemical model of the integrated planar solid oxide fuel cell (IP-SOFC). *Chemical Engineering* 102(1):61–69.
- [6] Donatelli R.U. 1990. Combustion turbine repowering at the Lauderdale plant. *ASME, International Gas Turbine Institute (Publication) IGTI* 5:201–206.
- [7] EG&G and G Technical Services Inc. 2004. *Fuel Cell Handbook*, 7th edition, U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory.
- [8] Gas turbine world: 2007 performance specs, 24 Ed. Publisher: Victor de Biasi.
- [9] Haseli Y., Dincer I. and Natre G.F. 2008. Thermodynamic modeling of a gas turbine cycle combined with a solid oxide fuel cell. *Hydrogen Energy* 33(20):5811–22.
- [10] Holtappels P., DeHaart L.G.J., Stimming, U., Vinke I.C. and Mogensen M. 1999. Reaction of CO/CO₂ gas mixtures on Ni-YSZ cermet electrode. *Appl. Electrochem.* 29:561–68.
- [11] Keegan K.M., Khaleel M., Chick L.A., Recknagle K., Simner S.P. and Diebler J. 2002. Analysis of a planar solid oxide fuel cell based automotive auxiliary power unit, *SAE Technical Paper Series* No. 2002-01-0413.
- [12] Kehlhofer R., Hannemann F., Stirnimann F. and Rukes B. 2009. *Combined-cycle gas and steam turbine power plants*. PennWell, 3rd ed. Oklahoma. USA. ISBN: 978-1-59370-168-0.
- [13] Kovacic J.M., Stoll H.G. 1990. Economics of repowering steam turbines. *National Engineer* 95 (9):27–37.
- [14] Matsuzaki Y. and Yasuda I. 2000. Electrochemical oxidation of H₂ and CO in a H₂-H₂O-CO-CO₂ system at the interface of a Ni-YSZ cermet electrode and YSZ electrolyte. *Electrochemistry Society* 147(5):1630–35.
- [15] Riensche E., Achenbach E., Froning D., Haines M.R., Heidug W.K., Lokurlu A. and Adrian S. 2000. Clean combined-cycle SOFC power plant–cell modeling and process analysis. *Power Sources* 86(1–2):404–410.
- [16] Rokni M. 2010a. Thermodynamic analysis of an integrated solid oxide fuel cell cycle with a Rankine cycle. *Energy Conversion and Management* 51(12):2724–32.
- [17] Rokni M. 2010b. Plant characteristics of an integrated solid oxide fuel cell and a steam cycle. *Energy* 35:4691–99.
- [18] Rokni M. 2012. Thermodynamic investigation of an integrated gasification plant with solid oxide fuel cell and steam cycles. *Green* 2:71–86.
- [19] Rokni M. 2013a. Thermodynamic analysis of SOFC (solid oxide fuel cell) – Stirling hybrid plants using alternative fuels. *Energy* 61:87–97.
- [20] Siemens. 2010. Siemens Energy. [Online]. <http://www.energy.siemens.com>
- [21] Smith J.M., Van Ness H.C. and Abbott M.M. 2005. *Introduction to Chemical Engineering Thermodynamics*, 7th edition, Boston:McGraw-Hill.
- [22] Termuehlen H. 1994. Repowering of steam power plants with gas turbines in the USA. *POWERGEN EUROPE* 4:199–212.
- [23] Zhu H. and Kee R.J. 2003. A general mathematical model for analyzing the performance of fuel-cell membrane-electrode assemblies. *Power Sources* 117:61–74.
- [24] Walters A.B. 1995. Power plant topping cycle repowering. *Energy Engineering: Journal of the Association of Energy Engineering* 92(5):49–71.
- [25] Waller H., Scherer V. and Scherer D. 1996. The GT26 gas turbine in a combined gas-steam turbine power plant: Repowering the Rheinhafen Steam Turbine Power Plant of the Badenwerk AG. *VGB PowerTech* 76(8):571–576.
- [26] Winnick J. 1997. *Chemical engineering thermodynamics*. John Wiley & Sons, New York.
- Wolowicz M., Milewski J., Badyda K. 2012. Feedwater repowering of 800 MW supercritical steam power plant. *Power Technologies* 92(2):127–134.